DETAILED WORK PLAN

Compaction Equipment – Granular Soil Interaction

Historical compaction operations of soils has depended on relationships and procedures captured by R. Proctor back in the 1930's and further described by Olson (1963). The classic relationship of dry density plotted as a function of moisture content at a single compactive energy is shown in Figure 1. This figure also provides the zero-air-voids curve and the common compaction specification of 90% relative compaction. The compaction of soils either at wet or dry of optimum creates different internal structures that yield different engineering behavior. For example, compation wet of optimum creates soils structures that favor low permeability while compaction dry of optimum creates soils structures with greater shear strength and enhanced side stability (Daniel and Benson 1990). Therefore both dry density and water content are important in the performance of compacted soils. Furthermore, Figure 1 also presents a plot showing the effects of moisture content and strain level on the low-strain modulus. Under normal highway pavement system use, the compacted materials increase their moisture content or are exposed to higher strain levels due to traffic loads, this may cause a decrease of the loading capacity of the embankments.

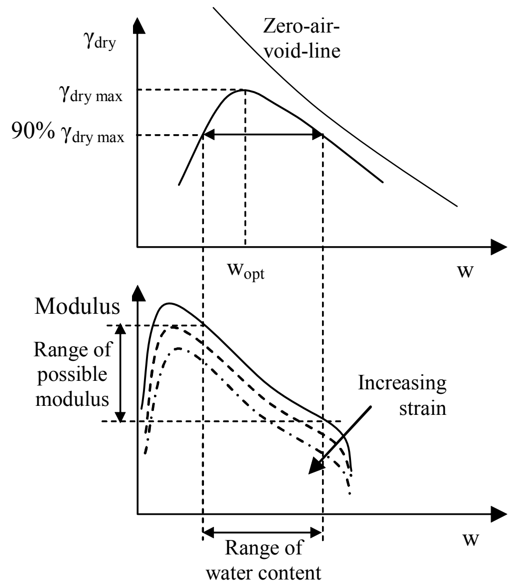

Figure 1: Typical Proctor results and the effect of water content change on the soil modulus.

The combined effect of strain level, soil texture, and changing water content in compacted soils make the interpretation of dynamic-based measurements for the evaluation of quality control of compaction operation and energy difficult. Furthermore, lifts of compacted soils yield non-uniform modulus and distribution in depth due to increasing confining pressure and non-homogeneous stress distribution under the compaction equipment (Winter and Clarke 2002 – see also Figure 2). When all these parameters are combined, the analysis and correlation of results becomes less clear and in some cases very different. Therefore, any testing program developed to estimate the optimal lift thickness and compaction depths must address the behavior of soils, the characteristics of traditional QC/QA tests, and an evaluation of the performance of compaction equipment and measured parameters. This proposal addresses all these elements by independently assessing received energy by the compacted soil at different depths, the response of different soils, and the mapping between on-the-flight measured parameters (particle acceleration and velocity) and traditional engineering measurements (e.g., surface stiffness,

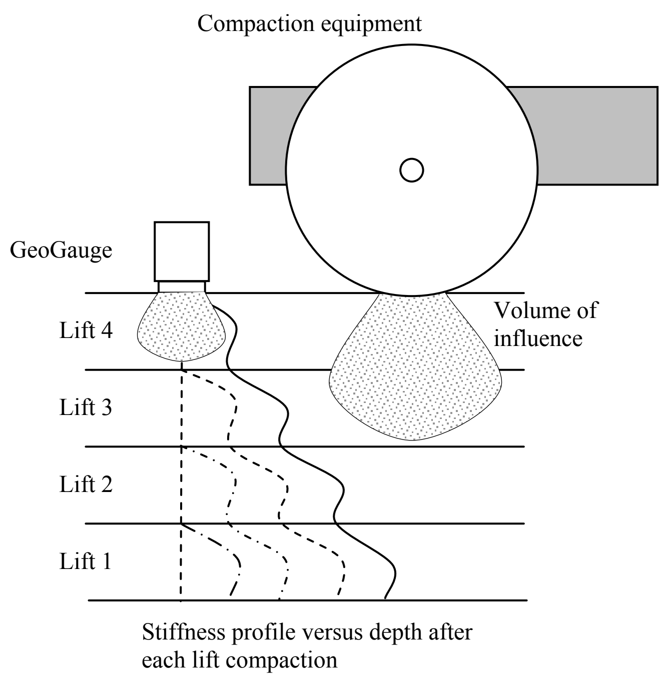

Figure 2: Effect of increasing compaction lifts on the modulus and on the results of dynamic based measurements.

dynamic cone penetration, and density measurements versus lift depths).

The proposed work plan will be divided in five phases:

I. Overall literature review
II. Theoretical/numerical and experimental evaluation of compaction efforts
III. Development of methodology to evaluate the response and effect of compaction operations in the field
IV. Establish correlations between experimental data and theoretical/ numerical predictive models
V. Draft recommendations for optimum lift thickness in Wisconsin embankment construction

Phase I – Literature Review: This phase will include a review of the state of the art compaction research, leading DOT's practices and policies, and the evaluation of modern compaction equipment specifications (emphasis will be placed in the compaction equipment used in the Wisconsin construction market). This literature review will summarize not only the practices but also the reasoning in the selection of lift thicknesses adopted by a number of leading departments of transportation. Special emphasis will be placed in the review of practices recommended for intelligent compaction operations as this new technology uses energy measurements to evaluate the effectiveness of the compaction operations (Briaud and Seo 2003; Peterson 2005; White et al. 2006).

Phase II - Theoretical/numerical and experimental evaluation of compaction efforts: Using the information collected during the development of Phase I, the research team will perform theoretical/numerical studies to evaluate the response of different soils to compactive efforts. The parameters to be studied include effect of compactor geometry versus relative depth (i.e., depth/compactor width), applied compactor energy, vibration frequency, and soil properties (i.e., texture, water content, and plasticity index). The theoretical and numerical studies will provide the base for the understanding of the interaction of the different compaction operation parameters. These studies will be also used to determine the number of field studies by emphasizing only on the dominant controlling parameters. Available finite element codes such as PLAXIS will be employed in the analysis.

Phase III - Evaluation of the response and effect of compaction operations on actual embankment construction operations: This phase will include the development of proper methodologies to measure lift responses under actual embankment construction conditions. It will include testing sensors to evaluate level moisture content, compaction effectiveness and compative energy versus depth. These sensors measurements will be combined with more traditional surface measurements to evaluate the quality of the compaction operations. These more traditional measurements will include sand cone, nuclear densimeter, Soil Stiffness

Gauge (SSG), and dynamic cone penetration (DCP). When possible, measurements will be done at different depths by successively removing surface materials from each of the lifts.

The combination of different measurement techniques and sensors present several challenges. One of the main difficulties in the design of the data acquisition systems for the evaluation of density/moisture condition and energy versus depth during compaction operations, respectively, are two very different acquisition rates: one is low-rate: i.e., density/moisture measurements (rate as low as once per hour) and the other one is high rate: i.e., pressure and acceleration (at a rate of about 10 kHz). To solve this problem, the research team proposes to collect moisture data with one data acquisition system while collecting the dynamic, high sampling rate data with another data acquisition system. If needed, to reduce memory requirements, the high sampling rate data may be processed on site and only the processed values may be recorded (e.g., maximum and minimum amplitudes, frequency content, etc.). Statistical processing may also be employed.

Moisture Probes: TDR Probes and other sensors. Time domain reflectometry (TDR) probes can, with proper calibration, be used to monitor the volumetric water content in soils (Benson and Bosscher 1999; Jones et al. 2001). These probes measure the electromagnetic wave velocity of soils surrounding the probes. The speed of the ELM wave is controlled by the volume of water in the material. That is, the TDR technique can be used to monitor the volumetric water content. The TDR probes will be placed in the soil lift before compaction to monitor changes in the water content and to help in the estimation of the changes in the strength and stiffness of the soil. Campbell TDR sensors are very commonly used in the transportation engineering applications and by the UW GeoEngineering group (Figure 3). These sensors are readily available at UW GeoEngineering laboratories.

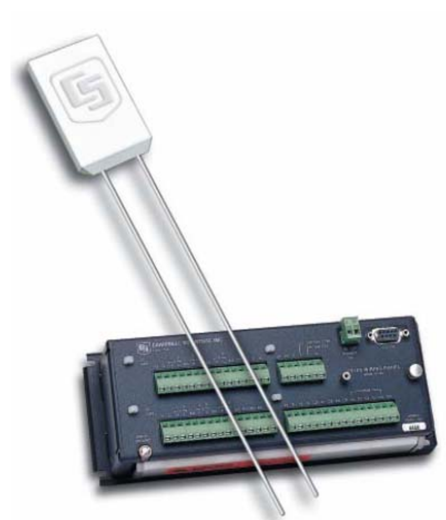

Figure 3: Campbell TDR sensor and multiplexer

MEMS Accelerometers. Miniature Electro-Mechanical Systems (MEMS – Figure 4) accelerometers are inexpensive sensors (< $25 each for dual axis accelerometers) that can be embedded in compacted soils to help monitoring particle acceleration and

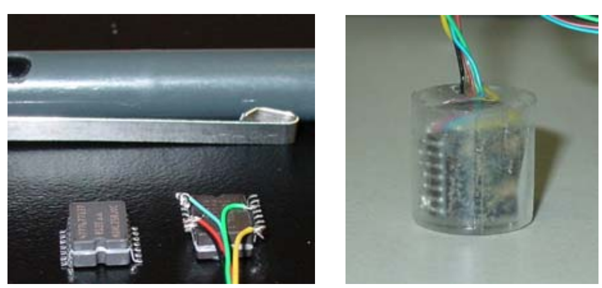

Figure 4: Analog Devices iMEMS accelerometer Coated accelerometer for environmental and mechanical protection (Hoffman et al. 2006).

displacement and stiffness over time. Because of the robustness of the measurement circuit and the low cost of these sensors, MEMS can be used to provide redundant information to the other monitoring systems. Furthermore, MEMS accelerometers can be used to monitor relative internal energy received by the soil by calculating the soils particle velocity and establishing a volume of influence of the compacted soils. Figure 5 shows typical responses of MEMS buried in a soil tank and excited at the surface. An arrangement of up to 16 accelerometers both in the vertical and horizontal planes will be used to monitor the received compacted energy in 3D and will estimate the energy distribution and response of soils during vibration operations.

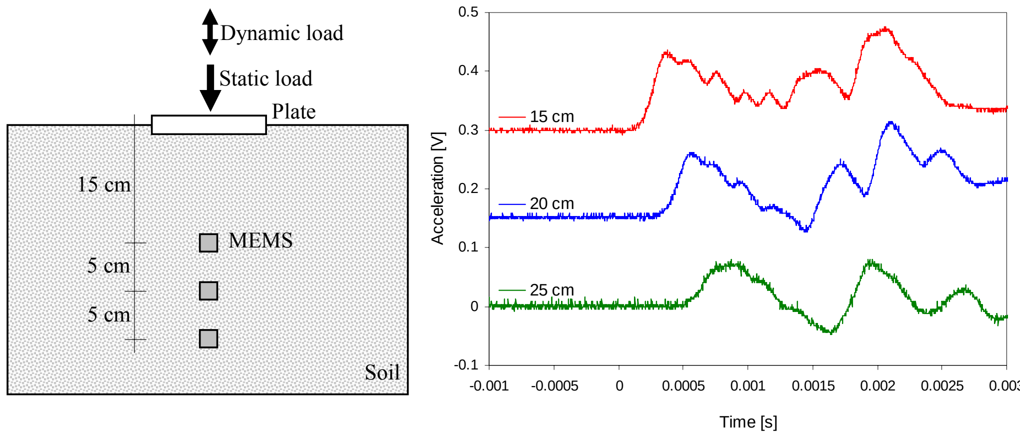

Figure 5: MEMS responses after a dynamic excitation at the surface of a granular soil specimen.

Earth Pressure Cells. The main function of these cells is to monitor the pressure in the granular sub-base caused by the compactors. There are several technical issues and concerns related to response of these cells. For example: the dynamic response of the cell must be much higher than the time period of the acting forces and the size of the cell needs to be much larger than the main particle size to be able to measure the “average” of the total stresses. For these reasons, the earth pressure cells will be used to supplement the results obtained with MEMS to evaluate depth of influence of compactor rollers.

Field Test Plan: The field test plan will consist of compacting typical materials for embankment construction. The testing site will be offered by Hoffman Construction Co. for this project (see attached letter of support). Two primary soils will be tested: fine-grained (low plasticity clay and silt) and granular (sand). Granular materials for base or subbase construction are of less concern, because the pavement design generally limits the base or subbase layer not to exceed one foot in Wisconsin. Constructions of embankments of more than one foot are typically encountered during roadway reconstruction in which the roadway profile is changed to improve the safety, drainage, or vertical clearance of structure.

The soils for embankment construction seldom are at their optimum moisture contents. The degree of compaction is of concern when the moisture content is on either dry or wet side of optimum moisture content, especially the dry side. This situation has been witnessed by the research team in the field. When soils were compacted on the dry side of optimum moisture content, significant settlement happened after the soil become wet. Therefore, it is critical to measure the degree of compaction on both sides of optimum moisture content.

The test plan is as follows:

1. Determine optimum moisture contents and dry densities of the two types of soils. It is expected that the compaction of the granular soil to be less sensitive to moisture than fine-grained soils. Fine grained soils will show significant dependency on moisture content.
2. Fresh soil will be loaded in a truck, dumped on the edge of the test section, and spread on the test section using a dozer. This will most accurately represent the way in which material is placed on actual projects. The test section will be 150-ft long and one-lane wide. For each lift thickness, soil type, and compactor type; a new section will be created with fresh soil. Thus there will be 48 test sections constructed. The test sections will be compacted using the following compaction equipment: Caterpillar CS563 smooth-drum vibratory roller, Caterpillar CP563 sheepsfoot roller, and Caterpillar 824C rubber-tired roller. These are the three rollers that are most commonly used in construction in Wisconsin. These compactors in the construction site will be made available by Hoffman Construction Company (see attached letter of support).
3. Spread the soil at the specified moisture content and the specified lift thickness starting at 8-in lift in each test section (See Table 1 for the testing combination). Compact the soil lift using the appropriate roller (See Table 1).
4. Measure the volumetric water content before and after each compactor roller pass. During the compactive energy excitation, collect soil dynamic data using the MEMS accelerometers and the earth pressure cells to estimate the delivered energy and the depth of influence of the compaction rollers.
5. Determine the Dynamic cone penetration index (DPI) and the Soil Stiffness Gauge (SSG) before compaction and after each pass of roller up to 10 passes (more passes may not be necessary – see Tran and Muro 2004). The DPI and SSG readings will be collected at three different locations in the center 50-ft long section of the test section where the compaction conditions are expected to be uniform.

Table 1: Field testing combination

1 - 10 passes			
Fine-grained Soil		**Coarse-grained Soil**	
Sheepsfoot Roller	**Rubber-tired Roller**	**Smooth-drum Vibratory Roller**	**Rubber-tired Roller**
Dry (4-5% < w_{op}) 8”, 12”, 16”, 20” lift	Dry (4-5% < w_{op}) 8”, 12”, 16”, 20” lift	Dry (4-5% < w_{op}) 8”, 12”, 16”, 20” lift	Dry (4-5% < w_{op}) 8”, 12”, 16”, 20” lift
Optimum 8”, 12”, 16”, 20” lift	Optimum 8”, 12”, 16”, 20” lift	Optimum 8”, 12”, 16”, 20” lift	Optimum 8”, 12”, 16”, 20” lift
Wet (4-5% > w_{op}) 8”, 12”, 16”, 20” lift	Wet (4-5% > w_{op}) 8”, 12”, 16”, 20” lift	Wet (4-5% > w_{op}) 8”, 12”, 16”, 20” lift	Wet (4-5% > w_{op}) 8”, 12”, 16”, 20” lift

6. At the end of 10 passes, determine the in situ density of the top 4 inches with sand cone test. Remove the top 4 inches and determine the density of the bottom 4 inches. Supplement these readings with nuclear density but zone of sampling of nuclear density is not controllable and may give ambiguous results. Also make SSG measurements at each level. Again the same issue of ambiguity may exist as it is reported that SSG reading samples a zone of 15 inches deep (see for example, Sawangsuriya et al. 2002).
7. The sequence described above will be repeated for the specified water content and lift thicknesses incremented at 4 inches up to 20 inches. If warranted by the collected data, lift thickness up to 30 inches will be considered.

Phase IV - Establish correlations between experimental data and theoretical/numerical predictive models: The data obtained in phases II and III will be used to establish correlations between the field measurements and the theoretical/numerical predictive models to estimate compaction energy and efficiency at depth for different soils and lift thicknesses. The results of the phase will produce an objective analysis to determine an optimal lift thickness for embankment construction on WisDOT projects depending on the type, weight and energy of the compactor and the physical characteristics of the compacted soils.

Phase V - Draft recommendations for optimum lift thickness: Based on the analysis of the theoretical/analytical and field experimental results recommendation for changes in the WisDOT optimum lift thicknesses. The proposed changes will be submitted to WisDOT officials for their incorporation into the WisDOT Standard Specifications for Highway and Structure Construction. However the decision and the implementation of the changes to the Standard Specification will not be part of this proposed research program.

5. WORK TIME SCHEDULE

Table 2: Project time schedule

Phase Number	1.5 Years (18 months)					
	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 5	Quarter 6
Phase I						
Phase II						
Phase III						
Phase IV						
Phase V						

6. REPORTS

The research team will present the WHRP Director with a total of five quarterly reports and a final report. The quarterly reports will provide the WHRP and WisDOT officials with an opportunity to review the progress of the research program and to give input about issues that are important in the construction of embankments in the State of Wisconsin. The submission of the final report will include a presentation at the WisDOT headquarters to help provide an informal forum for communication and discussion between the research team and the technical panel.

A draft final report documenting the entire research effort will be submitted to WisDOT for review at the end of the project. The draft and final reports will provide a comprehensive summary of research effort conducted. The final report will be prepared in accordance with the WisDOT Publication Guidelines. Finally, research results will be summarized in manuscripts and submitted as transportation/geotechnical conference and journal papers.